METHOD AND SYSTEM FOR PERFORMING SWEPT-WAVELENGTH MEASUREMENTS WITHIN AN OPTICAL SYSTEM INCORPORATING A REFERENCE RESONATOR

RELATED APPLICATIONS

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This application is a continuation-in part of U.S. Patent Application "METHOD AND SYSTEM FOR PERFORMING SWEPT-WAVELENGTH MEASUREMENTS WITHIN AN OPTICAL SYSTEM", Ser. No. 10/403,238, filed on March 28,2003, the specification of which is

10   incorporated herein by reference.

BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION

This invention relates to optical systems, and more

15   specifically, to a swept wavelength optical system that incorporates a coherent interference in both a reference path and a measurement path.

DESCRIPTION OF THE RELATED ART

20   Optical measurement systems, optical storage and retrieval systems and other optical systems may be limited by many factors, including illumination beam size, diffraction limit, detector noise, and resolution. The above-incorporated patent application discloses swept-wavelength techniques for enhancing

25   the performance of a variety of optical systems and improving

the resolution and sensitivity of optical technologies disclosed

therein. It would be further desirable to improve the

performance of the systems disclosed in the above-referenced

patent application, as well as other optical systems, in order

5   to further improve their performance.

The system phase accuracy requirement in some measurement

applications requires the wavelength control to meet or exceed

0.01% of the wavelength. Further, the resonator further

10   multiplies deviations in phase by the cavity length. With a

resonator length of 10000λ, phase control to 0.01% of the

wavelength dictates control of the illumination wavelength to

within 1 part in a hundred million or better, which is difficult

or impossible to stably achieve while maintaining high speed

15   operation by using a tunable illumination source and feedback

loop. The above-incorporated patent application overcomes this

barrier by providing a swept-wavelength system and method, that

do not require a phase-stable source. However, variations in

wavelength in terms of wavelength offset, drift and jitter are

20   difficult to manage in a swept-wavelength measurement system. In

particular, sufficiently agile sources are even more difficult

to stabilize than fixed-wavelength sources due to the rapidly

tunable nature of the source, as any cavity used to stabilize or

otherwise operate the laser must be tuned in the wavelength
sweeping process or must be sufficiently broadband that
stabilization is essentially not provided by the cavity.
Further, in an electrically swept illumination subsystem such as
5   those employing an electrically-tunable laser diode, electrical
noise in the control system or at the junction itself provides
phase variation or jitter.

     Therefore, it would be desirable to provide an alternative
10 method and system for swept-wavelength measurement that
overcomes the stability limitations of the illumination source.

SUMMARY OF THE INVENTION

The foregoing objectives are achieved in an optical system

and method and apparatus for optical measurement. The system

includes a swept-wavelength optical illumination subsystem, an

5   illumination coupler for producing a measurement beam and a

reference beam from an output of the optical illumination

source, a reference resonator for receiving the reference beam,

a measurement resonator for receiving the measurement beam, at

least two detectors, one optically coupled to the reference

10   resonator and one optically coupled to the measurement resonator

and a time-domain measurement system coupled to the detectors

for comparing detected optical signals received from the

detectors, so that the reference resonator measurement is used

to compensate for variations in the wavelength of the

15   illumination subsystem.

In particular, components of the time-domain analysis

provide information about changes in the wavelength of the

measurement by using the reference resonator swept-wavelength

20   response in comparison to the measurement resonator response.

The measured changes permit determination of variations in the

measurement wavelength and/or variations in the measurement

resonator, and can be used to provide feedback for adjusting the

illumination wavelength or effective cavity length of the measurement resonator.

The foregoing and other objects, features, and advantages of the invention will be apparent from the following, more particular, description of the preferred embodiment of the invention, as illustrated in the accompanying drawings.

Brief Description of the Drawings

Figure 1 is an illustration depicting an optical system in accordance with an embodiment of the present invention.

5   **Figure 2** is an illustration depicting another optical system in accordance with an embodiment of the present invention.

Figure 3 is a block diagram showing details within the

10   optical system of **Figure 2**.

Figure 4 is a graph depicting detected intensity measurements in an optical system in accordance with an embodiment of the present invention.

Description of Embodiments of the Invention

The above-incorporated parent application describes a swept-wavelength technique and system that can be used to improve the performance of various resonator-enhanced optical systems. However, the accuracy of the techniques disclosed in the above-incorporated parent application is limited by a number of factors, the primary limitation being uncertainty in the wavelength of the illumination source due to factors such as coherence and emission linewidth, changes in the active media refractive index and/or the laser's optical length. Metrologically, the illumination wavelength is the measurement etalon and due to the large number of wavelengths in a typical measurement path, a small change in wavelength has a large effect on the measured results. Therefore, the illumination source in an optical measurement system must typically be stabilized to a level of 10^{-8} wavelength or in some cases down to 10^{-9} wavelength through known techniques of cavity and/or laser control.

Tunable sources, such as those employed to provide swept-wavelength measurements are especially prone to variations and/or deviation from expected wavelength profiles, as the required agility of the source and the rate at which the

wavelength must be swept in essence determine a maximum "Q" of

the associated cavities. The resonators used within tunable

lasers have relatively lower Qs than fixed frequency sources and

the amount of wavelength jitter is consequently higher, causing

an enlarged linewidth (decreased temporal coherence). Further,

the electrically tunable lasers employed in swept-frequency

measurements are sensitive to noise, offset and drift in the

control voltage, which tends to increase the amount of jitter

and also adds an uncertainty in the illumination wavelength due

to offset and drift. Electrically tunable resonators, if such

are employed, are subject to the same variations, although non-

tuneable resonators are still prone to quantum and environmental

changes that affect the optical path length of the resonator.

The present invention provides a significant accuracy

improvement to the techniques disclosed in the above-

incorporated parent application that reduce the impact of

uncertainty in the optical illumination source wavelength and/or

the optical path length of the resonator. A second resonator is

employed so that differential analysis of the measured return

intensities of the resonator may be used to remove the above-

mentioned uncertainties from a measurement. As mentioned above

with respect to the illumination wavelength as the measurement

etalon, in the present invention, the reference is changed from the wavelength to an optical path length of a passive etalon. The passive etalon incorporated in the system of the present invention is a resonator having a very stable or predictable

5   optical path length. The passive etalon can be of the same order or identical to the measuring etalon, yielding a greatly reduced relative error.

The measurement techniques use a time domain detection

10   analysis that are applied to both a reference resonator and a measurement resonator. The present invention uses time domain analysis to determine changes in the effective length of the measurement resonator as related to the reference resonator length (rather than to the illumination wavelength), thereby

15   correcting for uncertainty in the illumination wavelength or other system variation by a time domain analysis of the reference resonator response. The present invention may also correct other measurements cavity changes mentioned in the above-incorporated parent application, such as when a surface of

20   the measurement resonator is a surface under measurement with features detected by the time domain analysis, such as reflectivity/absorption, polarization, scattering (e.g. surface roughness), and so forth.

A swept wavelength illumination source is used to vary the effective length of both the reference resonator and the measurement resonator through several discrete resonance points. The time domain relationship of each resonator's resonance

5   points contains information about the cavity length, as the spread of the resonance points (detectable as pulses or other variations in the time domain detected signal) varies with wavelength. Thus, both instantaneous changes in the detected signal time domain profile and the time domain profile it self

10   can be analyzed to determine cavity length, cavity length changes or both. The time domain profile can be examined (or initially detected) to find any combination of pulse position, pulse width, pulse height and pulse shape. The information from the time domain analysis can be used to determine cavity length,

15   resonance "Q" (which may indicate a gross variation in cavity length or a change in reflectivity/absorption/scattering, etc.)

With reference now to the figures, and in particular to **Figure 1,** an optical system in accordance with an embodiment of

20   the invention is depicted. An optical illumination source **S1** is swept in wavelength under the control of sweep control **C1.** Illumination source will generally be a laser diode having a tunable cavity, but other sweepable illumination sources may be

used such as broadband lasers having tuneable optical filters

for sweeping the filter passband to yield a swept-wavelength

illumination subsystem. A coupler **5** divides the output of

illumination source **S1** into a reference beam and a measurement

5   beam. The measurement beam is introduced to a measurement

resonator **R2** and the reference beam is introduced to a reference

resonator **R1**. Measurement resonator **R2** is inserted in a

measurement path of the optical system, and part of the resonant

structure may be a surface under measurement, so that the

10   response of resonator **R2** as measured by a return intensity as

detected by a detector **D2** is indicative of a characteristic of

the surface under measurement (e.g., surface height or

reflectivity). Also, a transmitted intensity through resonator

may alternatively be measured by detector **D2** (if detector **D2** is

15   positioned to measure the intensity of a beam transmitted

through resonator **R2**) or another detector may be used in concert

with detector **D2** to measure both transmitted and reflected

intensity from resonator **R2**.

20   While the response at detector **D2** may provide an indication

of the measured characteristics of a surface, uncertainty in the

wavelength of illumination source **S1**, or other variations in

path length of the measurement path will yield error

(deviations) in the response at detector **D2** from the desired or expected response. Reference resonator **R1** provides correction for the above-mentioned deviations by providing a stable reference response at detector **D1** from which the wavelength of

5   illumination source **S1** can be established at particular points in time. By processing the outputs of detectors **D1** and **D2** in a differential measurement that compensates for the above-mentioned variations, the resolution of the optical system is greatly enhanced.

10

Coupler **5** can have a ratio determined by the particular application. In general, only a small portion of the intensity of source **S1** need be coupled to reference resonator **R1**, as reference resonator can be designed so that a high level of

15   reflectivity is produced at maxima of the resonance waveform generated by the swept wavelength illumination. Measurement resonator **R2** may therefore advantageously use the higher illumination intensity coupled from coupler **5** in order to measure, for example, a surface having a high degree of

20   dispersion or a low reflectivity. Reference resonator **R1** can be a very stable resonator, as no moving parts or tunability is required for the reference resonator **R1**. Either resonator may be a Fabry-Perot resonator, or one may be Fabry-Perot and the other

another form of resonator. As reference resonator **R1** does not
require tuning or scanning, it may be made from temperature
stable materials in a solid housing and the size of resonator **R1**
may not be a critical factor, permitting mounting of reference
5   resonator **R1** outside of a scanning head that includes
measurement resonator **R2**.

Additional reference resonators (**R2A** coupled to detectors
D2A and having path lengths **L2A**) may be added to the system to
10   provide further improvement in reduction of measurement
uncertainty. In general, it may be desirable to have reference
resonators of differing but similar lengths in the system, since
the path length measurement sensitivity varies with the
illumination wavelength. For example, a number of reference
15   resonators **R2A** may be employed, each having a resonance peak
equally distributed within a half-wavelength of the expected
illumination wavelength, so that at least one of the resonators
will be operating near a region of highest sensitivity in the
resonator response. Alternatively, or in concert, similar
20   resonators may be used to determine variations in
characteristics of the reference resonators themselves (e.g.,
variations due to temperature, imposed electromagnetic fields

that affect the refractive index, mechanical strain and so
forth).

The propagation length in the system must be taken into
account, i.e., the differences between the reference optical
path and the measurement optical path from the point of
splitting in coupler **5**, so that phase differences between the
measurement beam and reference beam do not introduce significant
de-correlation of the wavelength variations and degrade the
accuracy of the measurements. A propagation path difference of
298mm introduces a time/phase shift of 1 nanosecond and
introduces a noticeable de-correlation of the wavelength
variations. Optical path matching techniques are well-known in
the art, so are not discussed herein.

With reference now to **Figure 2**, a surface or volume **12**
including features under detection or data that is being
extracted is illuminated by a tunable illumination subsystem **11**
that produces an illumination beam **17A** and a reference beam **17D**.
Illumination source **11A** is introduced to splitter **11B** which
divides the illumination source output into measurement
illumination beam **17A** and reference beam **17D**. A reflected beam
17B and/or a transmitted beam **17C** is detected by a detection

subsystem **13** (shown at two alternative positions), providing

measurement information or data extraction. A measurement

resonator **15, 15A** or **15B** is positioned within the optical path

of the illumination beam **17A,** reflected beam **17B** and/or

5   transmitted beam **17C.** Illumination subsystem **11** has at least a

swept-wavelength operating mode responsive to sweep control

circuit **16,** which sweeps illumination subsystem **11** through

multiple resonant points of resonator **15, 15A** or **15B.** An

analysis subsystem **14** determines a time-domain relationship

10   between the resonances encountered by sweeping the illumination

wavelength, and cavity length or changes in cavity length or

finesse of resonator **15, 15A** or **15B** are thereby determined. The

cavity length, finesse or changes therein may be used directly

as a measurement output where the cavity length provides the

15   desired measurement information. For example, in measurement

systems where the features of surface or volume under

measurement **12** cause variation in the cavity length of resonator

15, the information extracted by analysis subsystem **14** contains

the feature information.

20

Reference beam **17D** is introduced to reference resonator **19**

and the resulting intensity is detected by a second detection

subsystem **13A** that is further coupled to analysis subsystem **14.**

(Detection subsystem **13A** is shown as a reflection detector, but alternatively detection subsystem **13A** may be coupled to measure transmission through reference resonator **19.**) The intensity measured by detection subsystem **13A** is used to correct or

5 evaluate the intensity detected by detection subsystem **13** at each moment in time, so that variations of the wavelength of illumination source **11A** and/or variations in the path length of the measurement beam (including variations within resonators **15** **15A** and **15B** that are not due to the measurement function) can be

10 reduced or eliminated in the measurement output.

In an alternative closed-loop feedback control system embodiment, the optical system may subsequently be tuned at a predetermined operating point in a constant-wavelength mode of

15 illumination subsystem **11.** The operating wavelength may be determined in conformity with the response detected from reference resonator **19** or from both reference resonator **19** and measurement resonator **15, 15A** or **15B** to provide the desired characteristics at detection subsystem **13.**

20

In beam narrowing applications, resonator **15A** is employed to reduce the profile of illumination beam **17A.** Resonator **15A** may be included within illumination subsystem **11** or located

between illumination subsystem and surface **12** as shown.
Alternatively, or in combination, resonator **15** may be employed
at surface **12** to increase sensitivity of the optical system.
Resonator **15** includes a partially reflective surface **14**

5 positioned above surface **12** at a predetermined distance to
provide a predetermined resonance operating point, and may
include a lens **20** that maps a region of partially reflective
surface **14** to a region of surface of interest **12** improving the
resolution of resonator **15**. A similar resonant structure may be

10 employed within reference resonator **19**, including a lens, or
reference resonator **19** may be any other resonant structure as is
known in the art.

Detection subsystems **13** and **13A** provide information to

15 analysis subsystem **14** so that the time domain relationship of
resonance points can be determined, which is generally a pulse-
shaped variation in intensity level (which may be "dark" or
"gray" level) of an interferometric fringe detector. Analysis
subsystem **14** extracts information relating to one or more of the

20 pulse peak positions (and differences between pulse peak
positions), pulse width, pulse height and pulse shape.

Tuning of resonator **15**, **15A** or **15B** may or may not be implemented in systems in accordance with various embodiments of the present invention. Since the measurement system is capable of determining multiple resonance points and their time

5 relationships when illumination subsystem **11** is in swept-wavelength mode, it may not be necessary or desirable to provide other than a generally fixed cavity length for resonator **15**, **15A** or **15B** (ignoring the actual cavity length variations provided by surface under measurement **12**) and a well-established cavity

10 length for reference resonator **19**. However, when it is desirable to tune resonator **15**, **15A** or **15B**, tuning may be accomplished by various means as described in the above-incorporated parent application.

15   Tuning (including sweeping) of illumination source **11** may be accomplished by use of a broadband laser/tunable filter such as the external cavity laser (ECL) or semiconductor tunable lasers such as Distributed-feedback (DFB) lasers, distributed Bragg reflector (DBR) lasers and vertical cavity surface

20 emitting lasers (VCSEL).

Referring now to **Figure 3**, details of the detection and control systems in accordance with embodiments of the present

invention are depicted. Detection subsystems **13** and **13A** include

fringe selection optics **42** and **42A** that select the

interferometric detection point as the output to detectors **44**

and **44A**. Amplifiers **A1** and **A2** adjust the gain and offset of

5   detector **44** and **44A** outputs to provide a control signal to pulse

detection circuits **45** and **45A**. Pulse detection circuits **45** and

45A are designed to match the shape of the pulses received by

detection subsystems **13** and **13A**, which will generally follow the

shape of the Airy-function (for a linearly changing illumination

10   wavelength) that describes the characteristic response of the

resonator as shown in **Figure 4**. Pulse detection circuits **45** and

45A may employ matched filters or other correlation blocks, in

order to maximize the received signal-to-noise ratio in

conformity with a predictable pulse shape.

15

The outputs of detection subsystems **13** and **13A** enter peak

location determination block **46** within analysis subsystem **14**.

Peak location determination block **46** determines a time

relationship of multiple resonance peaks occurring in

20   measurement resonator **15**, **15A** or **15B** and reference resonator **19**

as the wavelength of illumination subsystem **11** is swept in

swept-wavelength mode. Peak location determination block may be

a threshold comparator, but preferably a partial response

detector or other precision pulse position estimation circuit having a characteristic suitably matched to the output of pulse detection circuits **45** and **45A.** Additionally, a maximum-likelihood detector may be included to further correlate the expected time locations of pulses as determined by the linearly-swept wavelength for a fixed cavity length, especially in applications where the time location set for a plurality of pulses is a non-contiguous functions, such as in optical detection systems using a reflector to form a resonator with the encoded surface, where detection subsystem **13** is attempting to discern and differentiate between two or more discrete cavity lengths.

A pulse shape determination block **46A** is also coupled to an output of detection subsystem **13** and may measure the width, height or other shape characteristic of pulses received by detection subsystem **13.** Width detection may be achieved using a threshold detection that measures the crossing points of a pulse through a particular threshold. Pulse symmetry may be detected by differentiating between the positive and negative transitions and comparing with the output of pulse shape determination block **46A.** Pulse height may be measured by one or more thresholds,

including analog-to-digital (A/D) conversion systems providing a
quasi-continuous measurement range of pulse height.

Also, particular shapes may be correlated or a correlation
to one or more predetermined shapes may be compared in order to
determine the presence or absence of features on a surface under
measurement or other measurement or optical data input to the
system. A cavity parameters determination block **48A** is coupled
to the output of pulse shape determination block **46A** for
determining cavity parameters as a function of the pulse shape,
such as reflectivity/absorption/scattering of a surface under
measurement taken as a function of pulse width determined by
pulse shape determination block.

Time differencing block **47** determines the differences
between the multiple resonant peaks for each detection subsystem
13 and **13A** so that a cavity length determination block **48** can
extract a cavity length or changes in cavity length of resonator
15, 15A or **15B** and a relative cavity length of reference
resonator **19**. The apparent cavity length of reference resonator
19, is modified by deviations in wavelength of illumination
subsystem **11** from the expected wavelength. By comparing the
measured cavity length to the known cavity length of reference

resonator **19**, the wavelength deviation can be established and used to correct the response of detection subsystem **13**, improving the resolution and accuracy of the measurement.

5   The corrected measurement resonator cavity length information or change information may be used directly as a measurement output, for example when one of the resonator surfaces is a surface under measurement and variations in the height of the surface under measurement is the desired

10   measurement or data detection output. A counter **49** is used to count the number of resonance points scanned through by the swept illumination wavelength and can be used to reset ramp generator **52** within sweep control circuit **16**. Counter **49** thus ensures that a constant number of resonance points is scanned.

15

As an alternative to direct measurement output from analysis subsystem **14** while illumination subsystem **11** is in swept-wavelength mode, a sample/hold or programmable tuning source **54** may be used to provide a constant-wavelength mode for

20   illumination source **11**. A switch **S1** provides selection of constant-wavelength mode vs. swept-wavelength mode and sample/hold may be used to sample a particular point in the ramp generator **52** sweep output corresponding to a particular

resonance operating point of reference resonator **19** (not

necessarily a resonance peak) or the wavelength of illumination

subsystem **11** may be programmed via a programmable register,

divider, divider/multiplier loop or other means. Such a

5   configuration provides open-loop control of the operating

wavelength of tunable illumination source **11** while in constant-

wavelength mode, but representing a highly accurate wavelength

as determined by the response of reference resonator **19**.

10   Referring now to **Figure 4**, detector **44** and **44A** output

signals (**50, 51**) as produced by embodiments of the present

invention are depicted over time as the illumination wavelength

is swept for the two resonators **15** (or **15A** or **15B**) and **19**. Sweep

50 shows that the measurement resonator path length is shorter

15   than the reference resonator path length, as the peaks are

farther apart. Without reference resonator **19** detector **44A**

response **51**, any uncertainty in illumination wavelength would

reduce the accuracy of an optical path length determination

based on waveform **50**. But, by correcting the position of the

20   peaks of waveform **50**, by compressing or expanding the time-scale

of the figure so that waveform **51** corresponds to the known

optical length of reference resonator **19**, the resulting

measurement of the optical length of resonator **15** (or **15A** or **15B**) can be determined.

The figure shows a detector **44** and **44A** output when the detector is positioned on a light-band fringe position. It is apparent from the figure, that the position of the intensity peaks (which may be translated to intensity nulls for dark-band detector positions) in time, varies with the cavity length as described above. Peak location determination block **46** determines the exact position of the peaks (or nulls for a dark-band detector position) and the spread of the peaks in time is used to determine the cavity length according to the analysis below.

The above-incorporated parent application shows an approximate mathematical relationship between the location of the peaks of the waveforms of **Figure** 4 and the optical length of the resonators. By determining a ratio between the measured cavity length of reference resonator **19** as presented by waveform **51**, and compressing or expanding the scale of waveform **50** by a corresponding amount, the optical length of resonator **15** (or **15A** or **15B**) can be determined. Alternatively, more precise calculations can be applied to determine sweep linearity deviations based on the known optical length of reference

resonator **19**, taking into account variations of higher order

than linear variation of optical path length with time.

While the invention has been particularly shown and

5 described with reference to the preferred embodiments thereof,

it will be understood by those skilled in the art that the

foregoing and other changes in form, and details may be made

therein without departing from the spirit and scope of the

invention.